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Energetic and environmental performance of three biomass upgrading processes integrated with a CHP plant

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HIGHLIGHTS

- We simulate CHP-integrated production of wood pellets, torrefied wood pellets and pyrolysis slurry.
- Integration increases operation hours and district heat output by up to 38% and 22%.
- Additionally installed equipment reduces yearly power generation by up to 7%.
- Wood pellet production performs best energetically and environmentally.
- Integrated concepts substantially reduce fuel consumption and CO_2 emissions.

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ABSTRACT

In order to react on future expected increased competition on restricted biomass resources, communal combined heat and power (CHP) plants can be integrated with biomass upgrading processes that add valuable products to the portfolio. In this paper, outgoing from a base case, the retrofit integration of production of wood pellets (WPs), torrefied wood pellets (TWPs) and wood fast pyrolysis slurry (PS) with an existing wood-fired CHP plant was simulated. Within the integration concept, free boiler capacity during times of low district heat demands is used to provide energy for the upgrading processes. By detailed part-load modelling, critical process parameters are discussed. With help of a multiperiod model of the heat duration curve, the work further shows the influence of the integration on plant operating hours, electricity production and biomass throughput. Environmental and energetic performance is assessed according to European standard EN 15603 and compared to the base case as well as to stand-alone production in two separate units.

The work shows that all three integration options are well possible within the operational limits of the CHP plant. Summarising, this work shows that integration of WP, TWP and PS production from biomass with a CHP plant by increasing the yearly boiler workload leads to improved primary energy efficiency, reduced CO_2 emissions, and, when compared to stand-alone production, also to substantial fuel savings.

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1. Introduction

CO_2 mitigation and increasing the security of energy supply require action towards a more sustainable energy supply based on local and renewable energy sources. EU directives on the promotion of energy from renewable sources (2009/28/EC) and on the promotion of cogeneration (2004/8/EC), for instance, call for a sustainably increased and efficient conversion of biomass for transport and energy applications. However, increased use of biomass increases competition on limited biomass resources which will influence negatively the economy of communal biomass-fired combined heat and power (CHP) plants. As CHP plants can provide both, a source for heat needed for thermal conversion of biomass as well as the district heating (DH) network as a sink for process waste heat, it looks promising to integrate basic biomass upgrading processes like fast pyrolysis, torrefaction and pelletisation with CHP plants. The upgraded products have a higher energy density and hence allow more sustainable transport to central installations [1]. Technologies applied for such upgrading are relatively simple and robust, and thus investment cost and system complexity are expected to be on a reasonable level, thus making it also interesting for local small to medium-scale (up to 50 MW thermal) solutions [1]. The upgraded products can be processed to e.g. biodiesel, ethanol, methanol, hydrogen or other chemicals [2], but also can be directly combusted for power and heat generation (see e.g. [3–5]).

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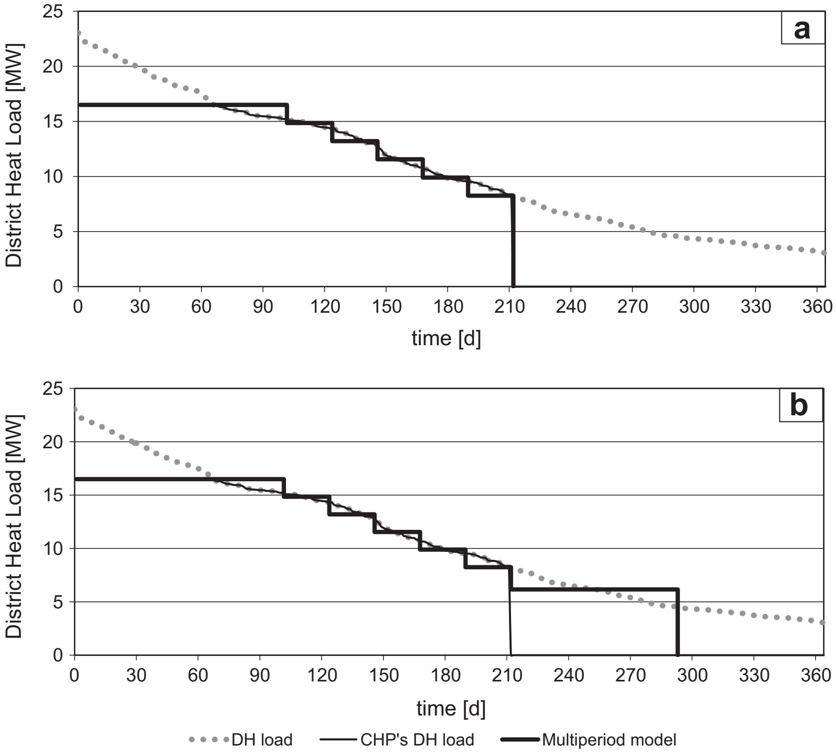

Fig. 1. DH load multiperiod model – (a) base case and (b) integrated case with subload (example).

Fig. 1 shows a typical heat duration curve of a DH network with one CHP unit under Nordic climate. It can be seen that the CHP plant is on full load only for 18% of the year, in shutdown for 42%, a period clearly exceeding the yearly maintenance time, and hence offers 300 days of underexploited boiler capacity for value creation by thermal and thermochemical upgrading processes.

Recent research points out the interest in and the importance of such integrated polygeneration systems [6–11]. In more detail, it has been shown by others [12–14] that gasification of biomass for syngas production integrated with a CHP based DH system is found technically feasible and economically advantageous.

Eriksson and Kjellström [15] concluded that wood-based ethanol production is most efficient when waste heat is used in an integrated CHP plant, but CO_2 mitigation costs were lowest for electricity-only generation in a combined cycle process. One concern is also the amount of heat produced in an economical-sized ethanol plant requiring a DH network with large free capacity.

Starfelt et al. [16] stated that retrofit integration of a CHP plant with bioethanol refining increases operation hours, electricity production and system efficiency, also in a short-term perspective [17]. Song et al. [18] integrated biomass drying with the polygeneration system investigated in [16] increasing overall efficiency and electricity generation by 3.1% and 5.5%, respectively. Other work of Song et al. [19] also found that integrating pellet production with an existing CHP plant increases power generation by up to 97% along with a significant reduction of global CO_2 emissions.

Wahlund et al. [3] showed that retrofit integration of pellet production with an existing communal CHP plant resulted in increased local biomass utilisation, operation hours, electricity production, efficiency and, along with decreased transport costs and CO_2 emissions of the considered energy system, to a higher income for the DH company.

Some of the work mentioned above only considers design case operation [13–15], or only one or two additional load points [3,16] are considered.

Starfelt et al. and Song et al. [17–19] considered part load operation for modelling the CHP-based polygeneration system, but process data has not been discussed.

Uslu et al. [1] compared the techno-economic performance of the stand-alone biomass pre-treatment steps pelletisation, torrefaction and fast pyrolysis and stated transport of pre-treated biomass as in general superior to untreated and further assessed torrefaction as most beneficial.

Hence part load operation and its mutual influence with the integration concept, especially on the operation parameters both on gas and steam side has not been modelled and analysed in detail. In addition, the influence and integration of fast pyrolysis and torrefaction with a CHP plant connected to a communal DH network has not been investigated.

The objective of this paper is to compare the retrofit-integration of a CHP plant of three different pre-treatment processes (biomass fast pyrolysis and production of biomass torrefaction pellets and wood pellets) and its effect on the energetic and environmental performance of the connected DH network. The work is based on simulation models considering auxiliary consumption of additional process components, part load behaviour of the power plant equipment (e.g. altering turbine and heat exchanger efficiencies) and changes in the heat load profile of the DH network. The aim is the highest possible product yield using the free boiler capacity in part loads under the condition that the DH demand is still fulfilled – electricity generation is hence left as a free variable. By detailed part-load modelling, critical process parameters for possible further process optimisation are obtained. With help of a multiperiod model of the DH network's heat duration curve, the work shows the influence of the integration on plant operating hours, electricity production and biomass throughput. Further environmental and energetic performance of the polygeneration system is assessed according to EN 15603 and compared to the base case. Also the difference to stand-alone production of wood pellets (WPs), torrefied wood pellets (TWPs) and fast pyrolysis slurry

(PS) concerning the CO_2 mitigation potential and primary energy savings is pointed out. Limitations of the study comprise of fixed conversion efficiencies of the pre-treatment processes and that cost data is not provided, since the focus of the work is on whether the integration concepts are possible within the operational limits of the CHP plant.

2. Process simulation

Simulation models of a CHP plant providing heat to a communal DH network were integrated with production of WP, TWP and PS, respectively. As the heat demand for the production is provided using free boiler capacity available during periods of lowered DH load, part load simulations have been carried out using a multiperiod model of the DH load. Pressure losses for modules are set to the default value of 0.01 bars for the design case and slightly vary with the load-dependent mass flows in part-load, due to the fixed geometry of the heat exchangers (see Section 2.2). The process models for WP, TWP and PS were calculated with constant conversion efficiencies, due to the fact that no detailed data on the part-load behaviour of the equipment described in this study could be found in the open literature. According to Meerman et al. [20] operation of such equipment is possible down to loads of 40–60% with certainly deteriorated efficiencies. For lower loads, exact sizing would be needed and the possibly a two-line approach might be necessary.

2.1. Multiperiod model of the district heat load

The CHP plant has been integrated with a virtual DH network. Therefore yearly data of a real DH network has been scaled so that the CHP plant provides 60% of the hourly peak demand of the DH network when on full load. The CHP plant is assumed to be shut off at 50% load which corresponds with 30% demand in the DH network. As stated in [21], those are common operating parameters for communal solid-fuel-fired CHP plants.

In order to represent the yearly production of the base-case plant a multiperiod DH load model was developed following a method used by Savola [21]. As presented in Fig. 1a two full load and five part load levels (90%, 80%, 70%, 60% and 50%) have been chosen to represent the heat duration curve. Operating time periods per part load level are set of equal length and – together with the two full load periods – match the total operation hours and yearly DH generation of 94.5 GW h as shown in Fig. 1a. The two full load periods are of same time and DH load but differ in their DH heat supply and return temperatures, as explained below.

All integration options allow for longer operation hours. This fact has been considered by firstly determining the lowest possible heat load (later referred to as min) and the related operation hour extension for the integrated CHP plant. Secondly the average DH load representing the respective operation time and heat production was computed and added as additional load level to the base case scenario (see Fig. 1b), later referred to as subload. DH supply and return temperatures are varied load-dependently from 110 to 80 °C and 83 to 36 °C, respectively. Therefore a linear correlation has been used with highest and lowest monthly average loads representing the highest and lowest supply and return temperatures. Additionally, the full load period was split in two parts of equal time length; one with a supply/return temperature profile of 110/83 °C and the other with 107/79 °C representing the varying temperatures in the DH network during CHP full load operation. The two full load periods are later referred to as 100% and 100% r.t., respectively. Simulation models for each load point are computed and fuel input and product yield were then iterated matching the required DH output, leaving electricity generation as free variable. For calculation of the annual production, DH demand not provided by the CHP plant is assumed to be generated in oil-fired heat-only boilers with a thermal efficiency of 0.93 [22].

2.2. Communal combined heat and power plant

A base case CHP plant with a bubbling fluidized bed boiler has been simulated in full and part load using the thermal power plant simulator Prosim (Fig. 2). The software is commercially available and showed its good reliability for preliminary design of natural gas and solid-fuel-fired power plants [21,24]. Prosim is a sequential modular process simulator and hence simulation models consist of process modules and streams. Once the process design is complete with all user data input, the software iterates mass and energy balances applying the Newton–Raphson method. In design case calculations it also calculates the physical and geometrical properties of the selected process modules. Those can be fixed for off-design calculations, i.e. when simulating part-load operation. Performance data of the CHP plant in design load was derived from [21] and adapted to the available DH data in terms of DH supply and return temperatures (Table 1).

Wood fuel composition was derived from the database PHYLLIS[1], its moisture set to a typical value of 50% [23] and the lower heating value (LHV) of the wood biomass to 7.93 MJ/kg (based on the Boie correlation as given in [25]).

2.3. Integration of wood pellets production

Pelletising is the mechanical densification of milled woody biomass to WP with a bulk density of approximately 650–700 kg/m^3 [1]. WP allow easier transport and offer more uniform fuel properties. Pelletising comprises of milling, drying, densification and fan cooling of the product. Electricity consumption for dryer operation, milling, pressing and fan cooling was set to 260 MJ/ton of wet wood [26] and is considered in the calculation of the CHP plant's net power output. The pelletising process requires an initial moisture content of approximately 10% and thus wood must be pre-dried. Continuous and fast drying of biomass to low moisture contents requires temperatures above the saturation temperature at given pressure due to the hygroscopic properties of biomass [23]. The dryer is modelled as a steam tube dryer and the heat consumption has been estimated to 3000 kJ/kg water evaporated [23]. Wood and hot flue gases are fed in the dryer (Fig. 3, module 22). If heat is available from the flue gases, they are cooled down to 143 °C which is the minimal flue gas temperature of the base case CHP plant, and together with the fully condensing steam provide the heat needed for the drying process. Paying attention to the retrofit situation, live steam is extracted (19), throttled to 10 bars (20) and further cooled to 190 °C (21) by spraying in the saturated water leaving the dryer (22). The dryer condensate is throttled to 2 bars (24), and sent to the feedwater tank (12).

The dryer load for each load point is given by the steam extraction rate required to match the DH network's heat demand. Thus, the maximum possible product yield requires highest possible fuel input since heat must also be provided to the drying process. Conversely, this means that the steam enthalpy exceeds the demand of the DH network because the boiler temperature is controlled by means of the evaporator- and superheater tubes in the boiler walls. If the heat input in the boiler is kept on a higher level than usual, the water amount needed to dissipate the heat from the boiler walls is increasing and consequently, in order to match the DH load, this heat must now be "dissipated" in the dryer (22).

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[1] PHYLLIS is a service provided by the Energy Research Centre of the Netherlands – URL: http://www.ecn.nl/phyllis, accessed 17.9.2009 [selected subgroups: untreated wood → birch and fir/pine/spruce].

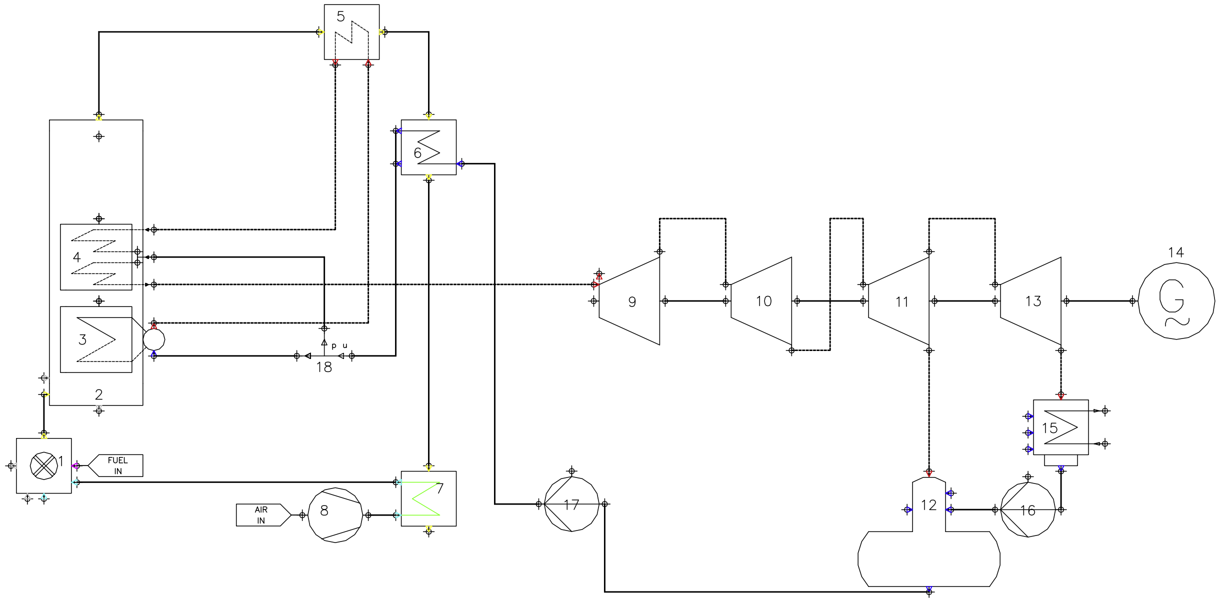


Fig. 2. Flowsheet model of the base case CHP plant.

Table 1
CHP plant design and wood fuel specifications.

Wood fuel				CHP plant – design data			
Ultimate analysis							
C	50.64	O	42.22	Fuel input	24.7 MW	Power output	5.21 MW
H	6.1	N	0.16	DH output	16.5 MW		
Ash	0.8	S	0.08	Live steam	60 bar, 510 °C	Condenser pressure	1.55 bar
M	50%	LHV	7.93	DH supply temp.	110 °C	DH return temp.	83 °C

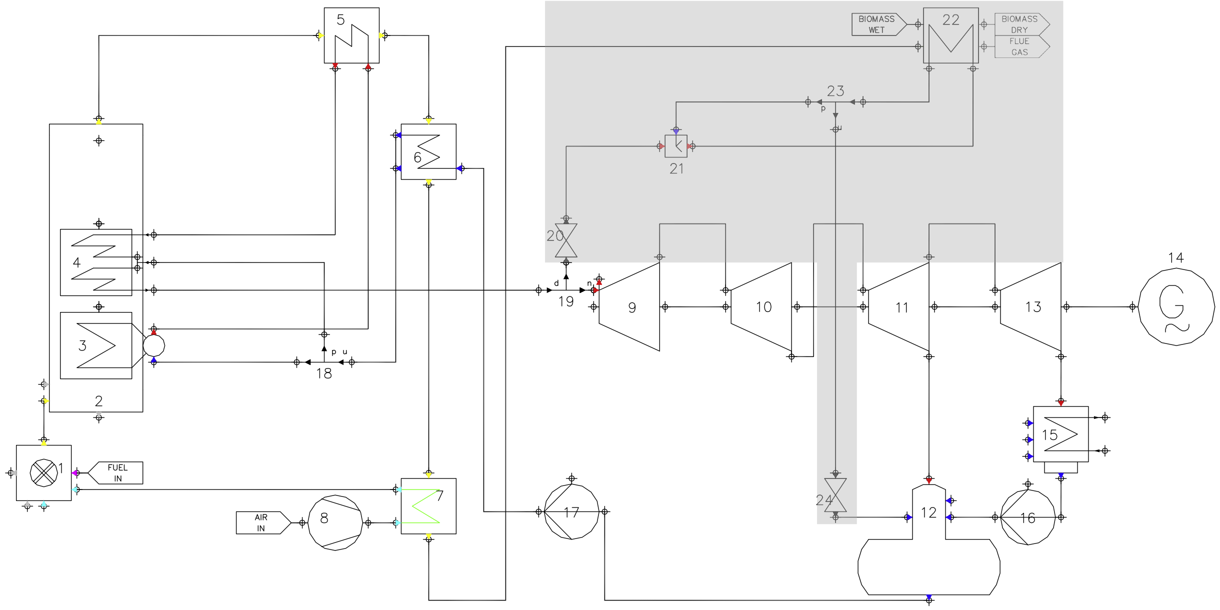


Fig. 3. Flowsheet of the CHP plant integrated with wood pellets production (added modules are highlighted in grey).

The DH load was matched by adjusting dryer load and fuel input. With this setup the WP yield constantly increases with the decrease of the DH levels down to 70% at full boiler load. The maximum flow off the dryer (and thus its capacity) is restricted by the pressure prevailing in the feedwater tank, which in turn is given by the extraction pressure after the third turbine stage (11). The pressure decreases with falling live steam parameters and steam mass flow. Hence, there is a pressure dependant maximum heat flow that can be fed into the feedwater tank until saturation state is reached for the mixture of the condensate from DH exchanger (15) and dryer (22). In order to overcome this restriction the feedwater tank pressure has been increased load-dependently to a maximum of 2 bars matching its design pressure (it should be noted that for increased pressures no steam is extracted anymore from the turbine). However, due to the reason mentioned above, for loads below 70% the heat that would need to be “dissipated” in the dryer (in order to match the DH load) would result in such a high dryer condensate heat flow, that it would bring the feedwater beyond saturation state. Hence, for those cases the boiler load was decreased gradually. With this control strategy the realisable lowest DH load decreases considerably which explains the increase in operation hours compared to the base case. In the base case the minimum load of 50% is given by the minimum fuel input required for stable combustion in the boiler. In all cases the boiler load is restricted to 100%. By this, the overload back-up capacity of the boiler is maintained.

2.4. Integration of torrefied wood pellets

Wood torrefaction is thermal treatment at temperatures in the range of 200–300 °C under atmospheric conditions in an inert atmosphere. By almost total water evaporation and decomposition of hemicellulose, in general, wet wood loses approximately 70% of its initial weight but only 10% of its energy. It thus increases the calorific value and torrefied wood has a higher energy density which improves its transport properties. Other advantages are: torrefied wood is easier to store due to its hydrophobic nature and it is more brittle and grinding energy can be reduced by 80%. Together with the fact that the thermal efficiency of subsequent gasification or combustion processes is increased due to the higher calorific value, it makes torrefied wood an interesting alternative for centralised CO_2-neutral power, heat and/or biofuel production [4].

Based on [4], the enthalpy of torrefaction of wood (20 °C, moisture 15%) at 280 °C has been estimated as 714 kJ/kg. Based on the LHV of the input wood, energy yields were set to 98.2% TWP and 5.1% gases, respectively. Cooling demand recovery remained unconsidered. The gas is thought to be co-fired in the boiler and its energy is subtracted from the boiler fuel input. Power consumption of dryer, torrefaction reactor and subsequent milling and pellet production is estimated to 340 MJ/ton wet wood [4,26].

The process has been integrated as follows (Fig. 4): prior to torrefaction, biomass is dried from 50% to 15% using the same dryer layout as described in Section 2.3. Heat for the actual torrefaction is provided by a flue gases split off (25) after the economizer (6). Flue gases have a load dependant temperature of 400–460 °C and are cooled down to 265 °C, providing heat indirectly to the torrefaction reactor, and are mixed (27) into the flue gas main flow before the air-preheater (7). This leads to a reduced flue gas temperature after the air-preheater (minimum 106.5 °C) which needs critical evaluation of potential corrosion. In this case flue gases are reheated in the dryer to the minimal temperature of the base case in order to get comparable results and to pay attention to potential corrosion risks. The heat extraction is modelled with the help of an additional evaporator (26). As explained in Section 2.3, the DH load is matched by simultaneous adjustment of the dryer input, the split-off required for torrefaction of the dried biomass and the reduction of the boiler load. The restriction set by the pressure prevailing in the feedwater tank has been dealt with as described in Section 2.3.

2.5. Integration of wood fast pyrolysis slurry

Biomass fast pyrolysis is the thermal conversion of preferably dry biomass in the absence of oxygen at temperatures of approximately 500 °C and atmospheric pressures. It yields pyrolysis gas, char and liquid in weight fractions of approximately 15% gas and char and 70% liquid, respectively. Roughly 90% of the energy is preserved in the mixture of char and oil, referred to as PS. Energy density of PS is high and potential applications for the product range from central power and heat generation to large-scale biofuel and chemical production [5].

Pyrolysis integration with a steam boiler is currently under development and seems to be technically and economically feasible [27,28].

Based on simulations done in Aspen+ [29], using mainly experimental results from [30], heat of pyrolysis of wood (20 °C, moisture 10%) has been computed to 1830 kJ/kg. This is in good accordance with data found in [31]. Based on the LHV of the input biomass, the process energy yields are 93.2% PS and 10.7% gases, respectively. The gas is thought to be co-fired in the boiler and hence its energy is subtracted from the boiler's fuel input. Following the bioliq® concept of the Karlsruhe Institute of Technology [32,33], slurry production requires milling and drying followed by a twin-screw pyrolysis reactor, a cyclone for solid separation and a colloid mixer for slurry preparation. Equipment's electricity consumption has been estimated to 270 MJ/ton wet wood [4,26,34,35].

The process has been integrated as follows (Fig. 5): prior to pyrolysis, biomass is dried from 50% to 10% moisture content using the same dryer layout as described in Section 2.3. Heat for the actual pyrolysis reaction is provided by a flue gases split off (25) after the boiler. Flue gas of a temperature of 850 °C is cooled down to 480 °C, providing heat indirectly to the pyrolysis reactor, and is mixed (27) into the flue gas main flow after the second superheater (5). The heat extraction itself is modelled by help of an additional evaporator (26). As explained in Section 2.3, the DH load is matched by simultaneous adjustment of dryer input, split-off required for pyrolysis of the dried biomass and reduction of the boiler load. The restriction set by the pressure prevailing in the feedwater tank has been dealt with as explained in Section 2.3.

2.6. Primary energy factor, CO_2 emission coefficient and stand-alone production

EU standard EN 15603 [36] defines the calculation of energy performance indicators for buildings in general and standard EN 15316-4-5 [37] for DH systems in particular. In this study, based on yearly generation data, primary energy factors (PEFs) and CO_2 emission coefficients (C_{CO2}) for the DH network are calculated applying the power-bonus method. Briefly, the PEF is the sum of all primary energy input to a DH network divided by the amount of DH delivered. It can hence be understood as the DH network's inverted efficiency. Correspondingly, C_{CO2} expresses all CO_2 emitted in order to deliver one unit of DH (for more details please refer e.g. to [38]). With the power bonus method the PEF of the DH network (f_{DHN}) has been calculated according to:

$$f_{\mathrm{DHN}} = \frac{Q_{\mathrm{Wood}} \cdot f_{\mathrm{Wood}} + Q_{\mathrm{HOB}} \cdot f_{\mathrm{HOB}} - P_{\mathrm{El}} \cdot f_{\mathrm{El}}}{Q_{\mathrm{DH}}} \tag{1}$$

where Q_{wood}, and Q_{HOB} are the LHV-based heat contained in wood and fuel of the heat-only-boiler (fuel oil) and P_{El} and Q_{DH} are power and DH heat generated, respectively. f_{DHN}, f_{Wood}, f_{HOB} and f_{El} are the corresponding PEFs. Values and references for f are given in Table 2 and represent the “energy history” of the fuels (extraction, transport, pre-treatment, etc.). f_{El} is defined as the PEF of the marginal electricity that is replaced by the power generated in the CHP plant. Discussion about which value to choose is on-going, varying from CHP power marginally replacing coal condensing power to national and regional efficiencies of power generation. In this study three scenarios were chosen (values given in Table 2): co-generated electricity replacing coal-condensing power, power produced with the Finnish average generation efficiency and power produced with the Norwegian average generation efficiency, representing a future

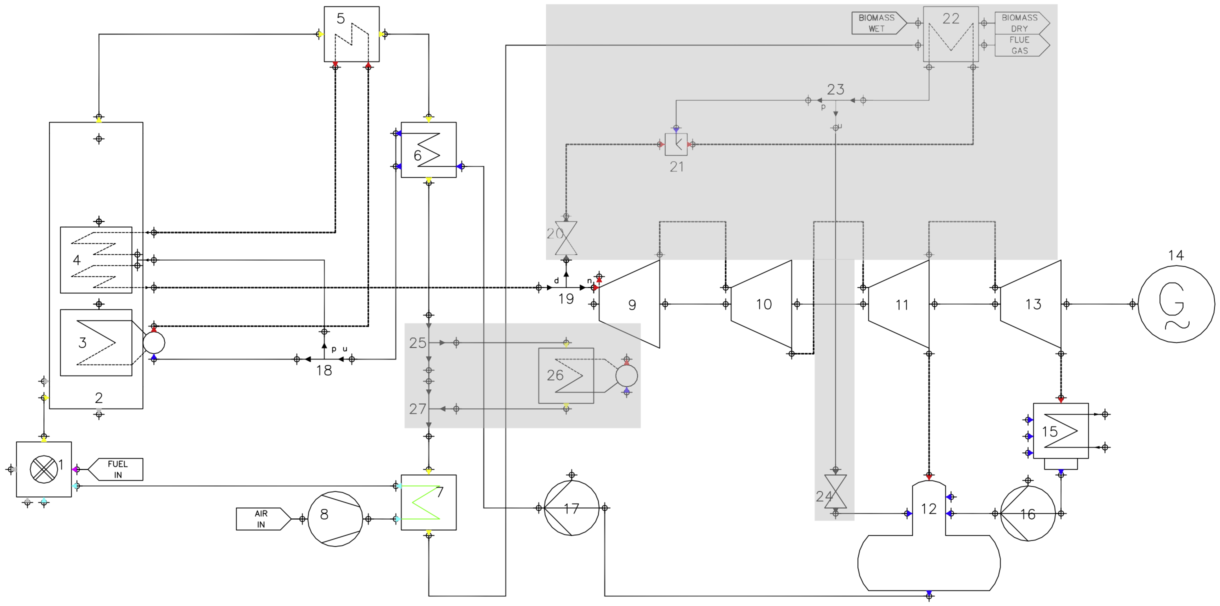


Fig. 4. Flowsheet of the CHP plant integrated with torrefied wood pellets production (added modules are highlighted in grey).

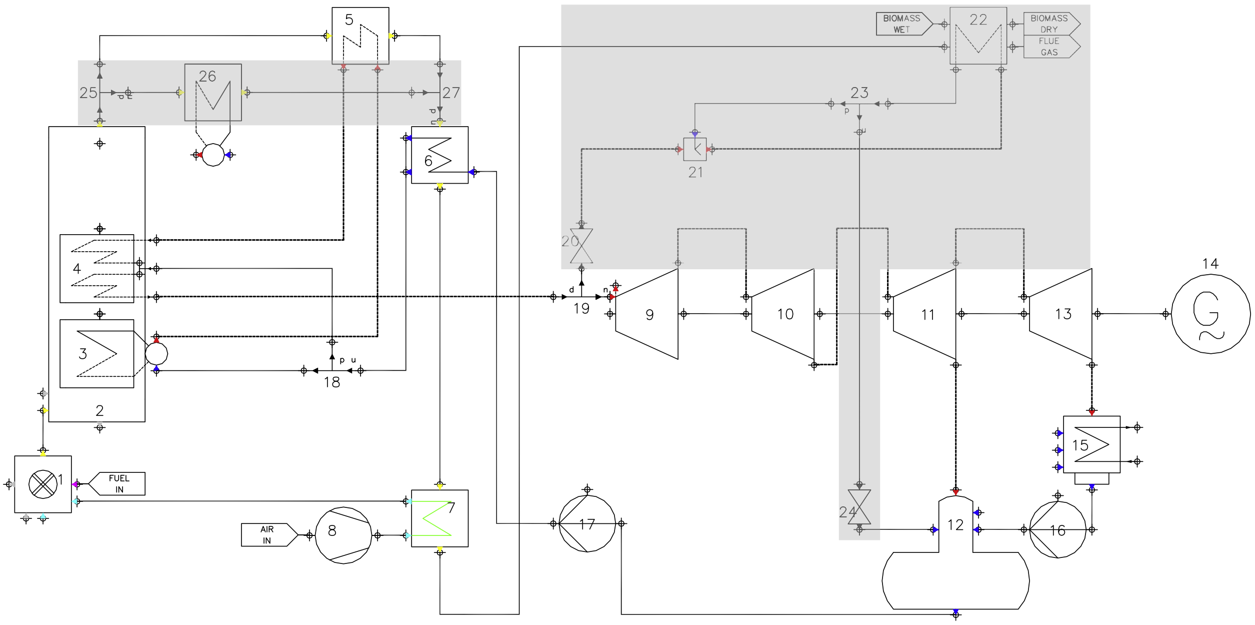


Fig. 5. Flowsheet of the CHP plant integrated with pyrolysis slurry production (added modules are highlighted in grey).

Table 2
Used primary energy factors and CO_2 emission factors.

Primary energy factor f (–)			CO_2 emission factor C_{CO2} (kg/MW h)		
f_{Wood}	1.09	[36]	$C_{CO2,Wood}$	14	[36]
f_{HOB}	1.35	[36]	$C_{CO2,HOB}$	330	[36]
f_{El}, coal	4.05	[36]	$C_{CO2,El}$ coal	1340	[36]
f_{El}, Finland	3.11	[39]	$C_{CO2,El}$ Finland	270	[39]
f_{El}, Norway	1.33	[39]	$C_{CO2,EL}$ Norway	9	[39]
f_{Prod}, coal	1.3	[36]	$C_{CO2,Prod}$ coal	414	[36]

case of an energy system with a high amount of renewable energy sources. As [37] does not define production of products other than electricity, the power bonus method has been extended by regarding the additional products as a "bonus" too. The PEF of the integrated options are thus calculated as:

$$f_{DHN} = \frac{Q_{Wood} \cdot f_{Wood} + Q_{HOB} \cdot f_{HOB} - P_{El} \cdot f_{El} - Q_{Prod} \cdot f_{Prod}}{Q_{DH}} \tag{2}$$

where Q_{Prod} is the heat contained in the products (WP, TWP, PS) and f_{Prod} is the PEF of the replacement. In this study we assume conservatively that the products would replace coal (see Table 2). Calculation of the C_{CO2} applies (1) and (2) replacing f_i with the corresponding C_{CO2}. Values for C_{CO2} are summarized in Table 2. Further spread sheet models of stand-alone production of PS, TWP and WP have been developed using the following assumptions: In all stand-alone-cases the dryer is assumed to be a flue gas heated drum dryer with a specific energy consumption of 3340 kJ/kg H_2O evaporated [23]. Heat of reaction for pyrolysis and torrefaction are set to 1830 and 714 kJ/kg dried biomass, respectively. Primary energy consumption and CO_2 emissions have been calculated with the factors given in Table 2. Flue gas and other losses have been neglected in order to facilitate a conservative comparison.

3. Results

For all three integration options pressures are influenced insignificantly, apart from pressure changes in the feedwater tank in part load, as explained in Section 2.3. However the influence on certain temperatures and mass flows is considerable and is described in more detail.

Firstly, on the steam side the main changes occur for PS integration. While in the other two options the live steam temperature can be maintained steady, it drops by up to 36.4 °C when PS production is integrated (see Fig. 6a). This is due to the high temperature heat provision for the pyrolysis which is taken from the flue gas by-passing the first superheater. This means that the heat exchange in the respective superheater deteriorates with the decreased mass flow and heat content of the flue gas. Compared to the base case, temperatures after superheater 1 are up to 83 °C lower (Fig. 6b). In general, due to the higher boiler loads the live steam mass flows are up to 50% higher (Fig. 6c), which results in only moderate reduction in gross power generation. In fact, if power consumption of the additional equipment is not considered, yearly electricity generation could be increased by 14–16%. For the steam cycle it also has to be mentioned that turbine exhaust temperatures, due to lower mass flow and exhaust pressure, exceed the base case's maximal temperature of 112.4 °C by 11.5 °C (Fig. 6d). Yet, the increase is modest and material problems can be excluded. The same accounts for increased feedwater temperatures after the economizer/before the boiler (Fig. 6e). For TWP integration, steam content in the feedwater can be up to 1.5% which likewise is not considered problematic. The higher feedwater temperatures for WP and TWP integration, respectively stems from the fact that, unlike in the base case where the feedwater tank pressure fluctuates with the load, saturation state in the feedwater tank is always reached at 2 bars by the recovered dryer condensate (see Section 2.3). In the case of PS integration the heat of the flue gas is not sufficient to reach the boiler's approach temperature (10 °C below T_{sat}); again due to the preceding provision of the heat of pyrolysis.

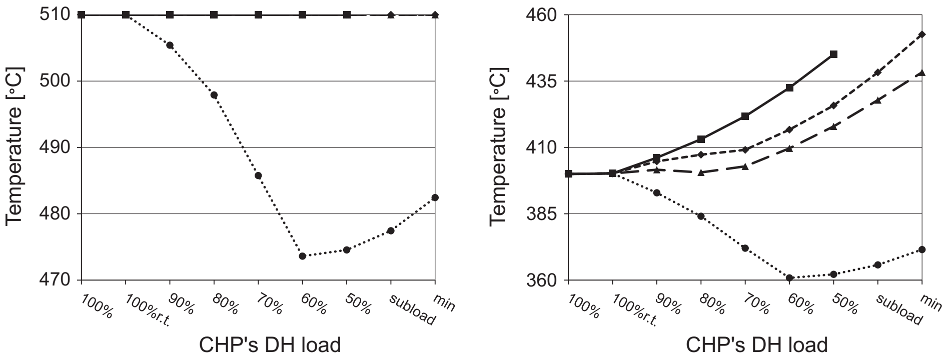
Secondly, on the flue gas side it can be seen that, as a result of the reaction heat allocation for pyrolysis and torrefaction, respectively, flue gas temperatures after the economizer/before the air-preheater are significantly (14–56 °C) lower for PS and TWP integration than for the base case (Fig. 6f). Consequently this results in reduced combustion air temperatures, alleviating power generation (Fig. 6g). Temperature reduction is most significant for TWP integration since reduced flue gas temperatures are only and fully accounted for in the air-preheater. In the case of PS integration, this burden is allocated to the economizer and the air-preheater lowering both temperatures somewhat. Further critical evaluation is needed for lowered flue gas temperatures after the air-preheater (Fig. 6h). In case of loads below approximately 69% for TWP integration the flue gas temperatures fall below the minimum temperature of the base case of 143 °C. The same accounts for PS integration if loads are below approx. 55%. Depending on the material and actual fuel chosen, potential corrosion risk must be ruled out before the implementation of such integration concepts. The process' overall mass and energy balance of the processes compared is not impeded, since the flue gas temperature after the dryer is fixed to 143 °C in order to assure comparability. In contrast to the above, integration of WP increases the temperatures of the flue gas and the preheated air due to higher boiler loads and an unchanged flue gas system layout.

Table 3 shows that annual operation hours can be increased by 25–38%. PS integration leads to maximum operation hours, since the large amount of heat taken from the flue gases decreases the influence of the restriction set by the feedwater tank pressure (see Section 2.3). By extended operation hours and the integrated product generation, yearly wood fuel input is increased by a factor of approximately 2.5 for all three cases studied. It is also observed that power generation decreases by 0.4–7%, which is mainly caused by the additional auxiliary power consumption. This decrease can be compensated only partly by longer operation hours. Steam extraction to the dryer and, in the case of PS, lower steam temperatures, contribute 5–23% of these losses. Product yields are highest for WP and lowest for PS production which is a result of the individual process' energy requirements. For instance, WP requires only drying to 10% whereas PS also requires heat for the actual pyrolysis reaction. The product yields hence also demonstrate the overall process efficiencies that are improved from 88.3% (base case) to 91.5% and 90.1% in the case of WP and TWP but reduced to 85.9% for PS. Product yields reach a maximum at 60–70% CHP load – until that operation point fuel input to the boiler is kept constant and therefore lower DH loads always mean higher product yields. When the maximum pressure of the feedwater tank is reached, the DH load must be controlled by reduction of the fuel input to the boiler which explains the lower product yields (see Section 2.3).

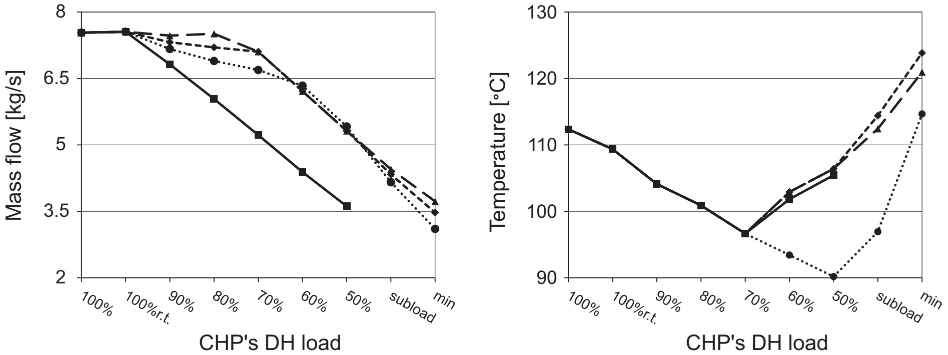
DH generation can be increased by 17–21% which reduces the heat only boiler fuel demand by 52–64%. Fig. 7a shows that, depending on the replaced electricity's PEF the DH network's PEF can be improved by up to 50% with WP integration. This is due to the WP's high product yield. In case of a high share of renewable electricity the improvement potential is lower, but with WP a PEF below 1 can be reached. It must be mentioned that EN 15603 defines that a PEF below one will be set to one. The same accounts for C_{CO2} values below zero – those will be set to zero. Still, reduction potential is considerable and integration of WP production performs best concerning the DH network's C_{CO2} (see Fig. 7b). Fig. 8a shows that, compared to stand-alone production of power, heat and bioproduct, it is always beneficial to integrate the upgrading process with the CHP plant. The integrated concepts allow fuel savings of 4.5–6.2% regardless of the type of fuel. When rating the fuels with their specific PEF, primary energy savings were calculated as 5.8–7.3%. The differences are more drastic when CO_2 emissions are considered. Savings of up to 45% are possible if PS is integrated with the CHP plant. This stems from the fact that by the integration a higher share of the DH demand is provided by the biofuel boiler (thus replacing fossil fuel in the heat-only-boilers) and the related 24 times higher specific CO_2 emissions of fuel oil when compared to biomass. This can also be seen in Fig. 8b, where it is shown that all integration concepts substantially reduce fossil fuel consumption by about 15%. It should be noted that calculated fuel savings do not consider fuel needed for electricity generation consumed by the auxiliary equipment of biomass processing (approximately 5.5 GW h). Interestingly, integration of TWP with CHP decreases the consumption of biofuel as well, whereas in the other two cases biofuel consumption slightly increases, but far below the decrease of fossil fuel. This demonstrates that waste heat of the bioprocesses is essentially used for DH.

4. Discussion

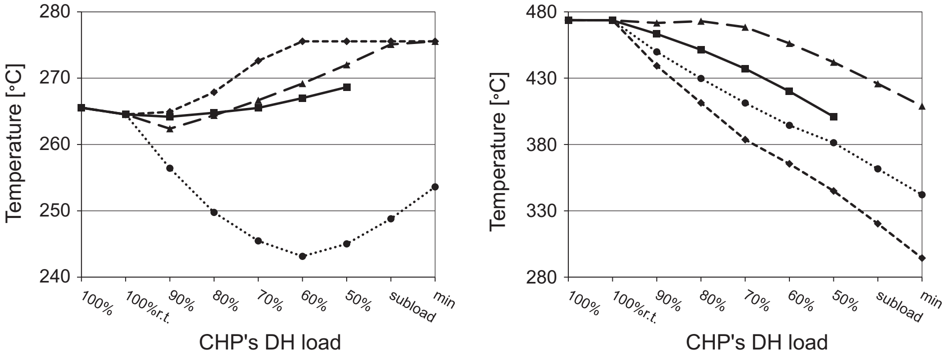
In general, results agree well with the work of others but differ concerning some aspects considered. Starfelt et al. [17], for instance, found that polygeneration of power, heat and lignocellulosic ethanol results in 17–23% higher electricity generation due to longer operation hours. However, in this case heat is only extracted from medium-pressure steam and auxiliary power for additional equipment might have been neglected which both would contribute to higher electricity generation if applied within



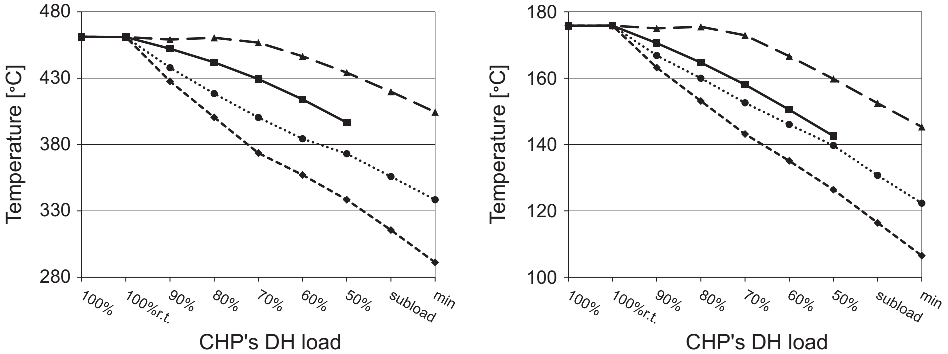
(a) Live steam temperature (b) Steam temperature after SH 1



(c) Live steam mass flow (d) Turbine exhaust temperature



(e) Feedwater temp. after economizer (f) Flue gas temp. after economizer



(g) Combustion air temperature (h) Flue gas temp. after air-preheater

■—■ Base Case ▲– –▲ CHP & WP ◆----◆ CHP & TWP ●·····● CHP & PS

Fig. 6. Comparison of operational parameters.

this study. Another reason for the higher power generation might lay in differences of the characteristics of the DH network layout. It can be easily shown that a heat duration curve with a smaller gradient will lead to extended operation hours. This relative

Table 3
Results of the multiperiod model.

CHP load		100%	100%r.t.	90%	80%	70%	60%	50%	Subload	Annual prod.
Base case										
Time	[h]	1220	1220	530	530	530	530	530		212 d
Fuel in	[MW]	24.7	24.9	22.5	19.9	17.3	14.5	11.9		106.1 GW h
District heat	[MW]	16.5	16.5	14.9	13.2	11.6	9.9	8.3		70.8 GW h
Net power	[MW]	5.2	5.3	5.0	4.5	3.8	3.1	2.5		22.9 GW h
Wood pellets (WPs)										
Time	[h]	1220	1220	530	530	530	530	530	1296	266 d
Fuel in	[MW]	24.7	24.9	40.1	53.4	57.8	52.4	46.3	39.9	265.7 GW h
District heat	[MW]	16.5	16.5	14.9	13.2	11.6	9.9	8.3	6.7	83.2 GW h
Net power	[MW]	5.2	5.3	4.4	3.4	2.6	1.9	1.5	1.1	22.2 GW h
WP	[MW]	0.0	0.0	17.6	32.7	39.4	36.7	33.2	29.1	137.7 GW h
Torrefied wood pellets (TWPs)										
Time	[h]	1220	1220	530	530	530	530	530	1488	274 d
Fuel in	[MW]	24.7	24.9	36.3	46.4	56.7	51.4	45.4	37.9	262.0 GW h
District heat	[MW]	16.5	16.5	14.9	13.2	11.6	9.9	8.3	6.6	84.1 GW h
Net power	[MW]	5.2	5.3	4.4	3.3	2.2	1.6	1.2	0.8	21.3 GW h
TWP	[MW]	0.0	0.0	13.7	25.6	37.7	35.2	31.8	27.0	130.7 GW h
Pyrolysis slurry (PS)										
Time	[h]	1220	1220	530	530	530	530	530	1944	293 d
Fuel in	[MW]	24.7	24.9	32.3	39.1	46.0	50.3	44.4	35.6	260.9 GW h
District heat	[MW]	16.5	16.5	14.9	13.2	11.6	9.9	8.3	6.2	86.1 GW h
Net power	[MW]	5.2	5.3	4.6	3.7	2.8	1.9	1.4	0.9	22.8 GW h
PS	[MW]	0.0	0.0	9.0	17.0	25.2	31.1	28.2	23.0	115.4 GW h

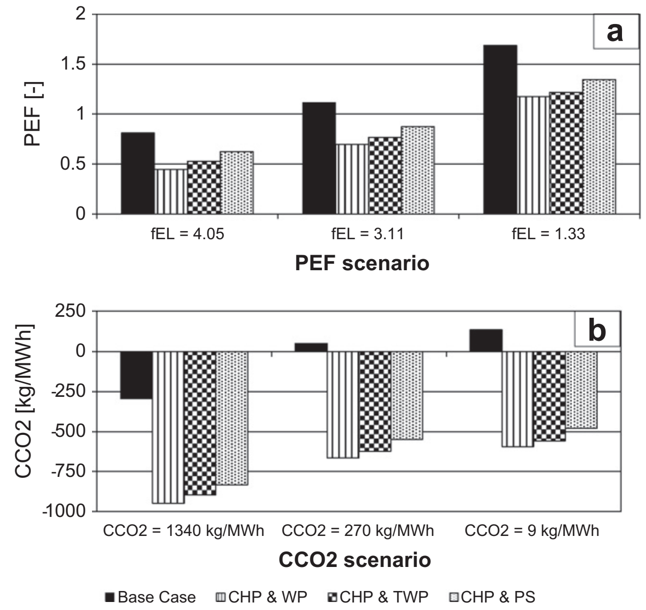


Fig. 7. Primary energy factors and CO_2 emission coefficients.

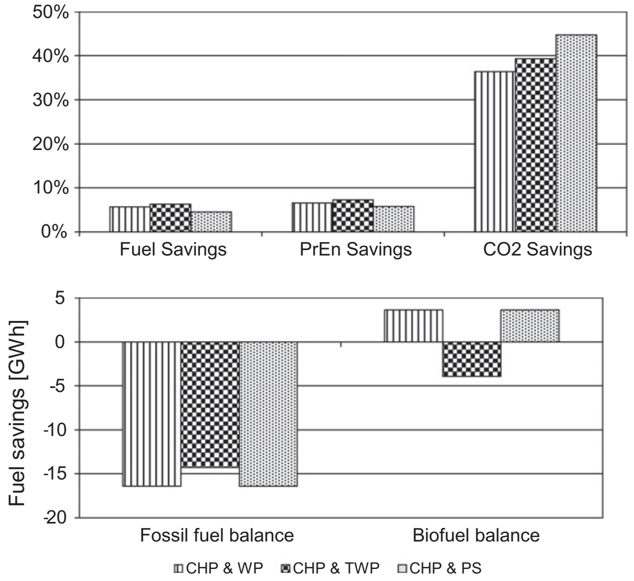


Fig. 8. Integrated concepts versus stand-alone.

operation hour extension can also be influenced if the CHP plant is designed for DH loads higher than 60%. Yet this consideration was not in the scope of [17] and such figures have not been reported. This potential influence also can be seen when the results are compared to [16] where a CHP plant is also integrated with ethanol production. This study gives a lower electricity generation for neglected auxiliary equipment. However, with the data discussed in [16] the influence of the heat duration curve and the CHP plant layout regarding the DH network on the additional electricity generation cannot be analysed since absolute values are not discussed.

Wahlund et al. [3] described WP production integrated with a CHP plant and concluded longer operation hours and increased electricity generation but a detailed process analysis was outside the focus of their study.

Taking also into consideration results gained by Song et al. [19] who likewise integrated WP production with CHP generation but found an increased electricity generation by 68–97%, it can be concluded that the DH network and the therewith related increase in operation hours has great influence on the power output of the integration concept. The same strong dependence can be expected for the environmental and energetic performance indicators as also being functions of the operation time.

It has also been shown that integrated production of WP, TWP and PS is always superior to stand-alone production concerning CO_2 emission and primary energy efficiency (lower primary energy input at constant product output), but also for the total fuel consumption. With reduced consumption of fossil fuel along with only slightly increased (PS and WP) or even decreased (TWP) biofuel input it deems rational that high reduction of fuel oil consumption will lead to lower fuel costs of the system considered.

The work shows that all three integration options are well possible within the operational limits of the CHP plant. Process control could be challenging, though, due to the DH load not being solely controlled by the boiler fuel input anymore but also by the heat requirement of the newly integrated processes. All options increase the annual operation hours, biomass throughput and product yield, respectively, as well as the DH network's energetic and environmental performance. Concerning product yield, energetic and environmental performance, integration of WP is most beneficial, followed by TWP. However, the LHV of TWP and PS are 12 and 16% higher than for wood; the volumetric energy density for PS is more than double the ones of TWP and WP. Therefore the resulting lower transport costs and advantages in possible subsequent fuel and chemical production could make PS a more valuable product than TWP or WP. Hence, further analysis including the processes' economics within extended system borders needs to be accomplished. Also an increased collection radius required for provision of the additional biomass should be included in such a consideration since it might worsen the economic as well as the environmental and energetic performance of the integrated energy system.

The results indicate that the integration concept proposed in this work can be improved process-wise mainly by expanding the steam in an additional turbine stage to the pressure level of the dryer before its use there and by increasing the pressure in the feedwater tank. The latter must be evaluated carefully since higher feedwater temperatures may lead to saturation conditions already in the economizer.

The very low PEFs and C_{CO2} that actually do not really allow for improvement must be seen against the background of the high renewable share of the DH network considered. For DH networks with higher PEFs being more dependent on fossil fuels, a higher margin of the benefits could be accounted for. Nonetheless, the work also shows that the choice of too high PEF_{El} and C_{CO2} can cause both, reduced improvement potential due to very low initial values and overestimation of the benefit in terms of C_{CO2} and PEF reduction. Hence, the choice of the PEF_{EL} and C_{CO2} can influence future DH and CHP strategies and further critical discussion is crucial.

5. Conclusions

According to the simulation results, integration is possible in between the operational limits of the CHP plant. Further, results show that yearly operation hours can be extended by 25–38%, resulting in 17.4–21.6% more district heat generated in CHP mode and, when upgraded biomass is considered too, in a 2.4–2.6 times higher total product output. Conversely, annual power output is decreased by 0.4–7% mainly due to the power requirements of the additionally installed equipment. Production of wood pellets gives highest product yield and, for the evaluation method used, performs best energetically and environmentally. This work shows that integration of wood pellets, torrefied wood pellets and pyrolysis slurry production from biomass with a CHP plant by increasing the yearly boiler workload leads to improved primary energy efficiency, reduced CO_2 emissions, and, when compared to stand-alone production, also to substantial fuel savings. However, a broader view combined with an economic evaluation might favour integration of torrefied wood pellets and/or pyrolysis slurry.

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